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# Determination of the $^7Be(p,\gamma)^8B$ cross section at astrophysical energies using a radioactive $^7Be$ ion beam

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A B S T R A C T

The reaction $^7Be(p,\gamma)^8B$ plays an important role in the Sun, where it determines the high energy component of the solar neutrino spectrum. The importance of this reaction triggered several experiments over the last decades. A combined analysis of their results produces an overall consistent picture for the energy dependence of the cross section, while an inflation of the quoted uncertainties is needed to accommodate the observed discrepancy in the absolute scale of the different data sets. The origin of this discrepancy needs to be understood for a reliable estimate of the astrophysical rate of $^7Be(p,\gamma)^8B$ and its uncertainty. In addition, there is a question about possible common systematic effects, considering that all measurements performed so far share the same experimental approach, i.e. an intense proton beam impinging on a $^7Be$ radioactive target. A direct measurement using a radioactive $^7Be$ ion beam on a pure hydrogen gas target has been since long envisioned as a way to improve the situation. First attempts showed the feasibility of an experiment based on the use of a recoil mass separator to collect reaction products with high efficiency, but failed to reach a useful statistical significance because of the low beam intensity. Here we present the results obtained using the intense $^7Be$ beam available at the Tandem Accelerator Laboratory at CIRCE, University of Campania, Italy coupled to the recoil mass separator ERNA in the energy range $E_{cm}$=367 to 812 keV. Our results are compatible only with a part of previous measurements, in particular those indicating a low value of the astrophysical S-factor at zero energy $S_{17}$, thus exacerbating the discrepancy between existing measurements. The analysis of our data together with the results of previous data provides an estimate $S_{17}(0)$=20.0±0.8 eV·b, where systematic uncertainties are inflated to obtain a statistically compatible data set.



## 1. Introduction

$^7Be$ is modestly produced in Big Bang Nucleosynthesis and in stellar hydrogen burning pp-chain when $^3He$ and $^4He$ nuclei are present at sufficiently high number density and temperature. In spite of its scarce abundance, however, $^7Be$ and its destruction through proton capture have a great importance in astrophysics. The rate of $^7Be(p,\gamma)^8B$ relative to the $^7Be$ electron capture decay rate in the Sun determines the ratio of $^7Be$ to $^8B$ solar neutrinos. These neutrinos represent a large fraction of the high energy

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solar neutrino flux, to which most of neutrino observatories are mainly sensitive (e.g. [1] and [2]). The importance of $^7Be(p,\gamma)^8B$ triggered several experiments to determine its cross section at the relevant energies for hydrogen burning ($E_{Sun} \approx 20$ keV). In our present understanding, the reaction $^7Be(p,\gamma)^8B$ at low energies is dominated by s- and d-wave direct capture into the ground state of $^8B$. The narrow resonance at E=630 keV[2] and resonances at higher energies have spin and parity assignments that do not allow interference with the direct capture component. A thorough review of the experimental status is reported in [3]: to our knowledge, no additional experimental information has been reported since its publication. All direct experiments producing results with sufficient precision to constrain astrophysical models used intense proton beams on radioactive targets, in most cases detecting the $\alpha$ particles emitted in the $\beta$ delayed decay of $^8B$. The uncertain target stoichiometry and its modification under beam bombardment as well as the difficulties to detect the reaction products are possibly the origin of the discrepancy between different data sets, that persists even if a selection based on a careful review of the experiments is done as proposed in [3]. An alternative approach using a radioactive ion beam and a hydrogen gas target was attempted in [4], and later in [5]. In both cases a recoil mass separator was employed to detect the $^8B$ recoils. However, those experiments reached an inadequate precision for astrophysical studies because of the low ion beam intensity ($\approx 10^7$ pps). We present here the results of a new experiment exploiting the same method with the much higher ion beam intensity available at the Tandem Accelerator Laboratory at CIRCE (Center for Isotopic Research on Cultural and Environmental heritage), Dept. of Mathematics and Physics, University of Campania, Italy, where a $^7Be$ ion beam is routinely produced [6] with an intensity up to $10^9$ pps.

## 2. Experimental setup and procedures

The experimental apparatus has been described elsewhere [7,8]. Shortly, the necessary $^7Be$ for the experiment is produced by proton bombardment of a metallic natural lithium target through the reaction $^7Li(p,n)^7Be$ at Atomki, Debrecen, Hungary and chemically separated to obtain cathodes for the Cs sputter negative ion source at CIRCE following the procedure described in [9]. $^7Be$ is extracted as a molecular ion $^7Be^{16}O^-$ from the ion source with an accompanying $^7Li^{16}O^-$ contamination and injected into the 3MV Pelletron Tandem accelerator, where molecules break up and form positive ions in the argon gas stripper at the high voltage terminal. The $^7Be$ kinetic energy at the terminal is equal to $m_{^7Be}/m_{^7BeO} \cdot U$ MeV, where U represents the terminal voltage in MV. The low energy at the terminal sets a limit of 2+ for the highest charge state that can be used to obtain a beam with adequate intensity for the present study, thus limiting the maximum beam energy to about 7 MeV. Finally, the mixed $^7Be$-$^7Li$ beam is analyzed, transported and focused onto a windowless hydrogen gas target [8], where the target gas is confined by two thin argon layers. The $^8B$ nuclei formed in the reaction emerge from the target at forward angles together with the beam ions in an intensity ratio of $10^{-11}$ to $10^{-13}$, depending on the cross section. The argon layer following the target allows ions to reach an equilibrium charge state distribution regardless of which position in the target they were formed. The mass separator ERNA (European Recoil mass Separator for Nuclear Astrophysics) filters out the beam ions, allowing the direct detection of the reaction products and the accompanying "leaky beam" ions in a final detector, a two-stage $\Delta E - E$ telescope [10] operated with isobutane, and capable of charge identification of the detected ions.

[2] when not otherwise specified, energies are to be intended in the center-of-mass system.

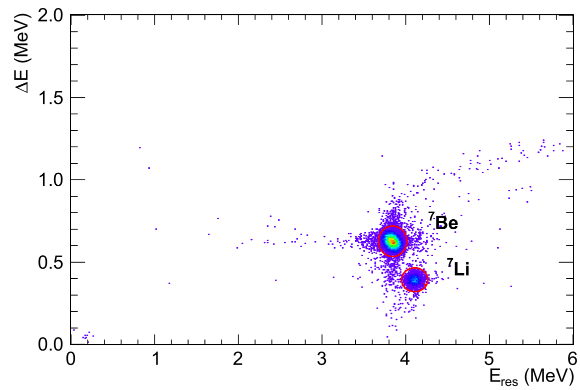


**Fig. 1.** Calibration matrix of the $\Delta E - E_{res}$ telescope using a mixed $^7Li$ and $^7Be$ beam at $E_{beam}$=5104 keV. The positions of both $^7Li$ and $^7Be$ ions are compared to 3-$\sigma$ contour plots obtained by means of a Monte Carlo simulation (see text for details).

The number of $^8B$ recoils $N_r$ observed in the final detector with an efficiency $\epsilon$ is given by:

$$N_r = N_b \cdot T_{RMS} \cdot \Phi_{q_r} \cdot \epsilon \cdot \int_{E_b-\Delta E_b}^{E_b} \frac{\sigma(E)}{|dE/dN_t|} dE, \quad (1)$$

where $N_b$ is the number of $^7Be$ projectiles, that is measured by the elastic scattering of beam ions in the target region, $\Phi_{q_r}$ is the probability of the charge state $q_r$ selected for the separation, $T_{RMS}$ is the transmission of the recoils from the target to the final detector. The interaction cross section $\sigma(E)$ is integrated over the beam energy loss in the target $\Delta E_b$ at the beam energy $E_b$, that is determined by the beam ions stopping power in the target $\frac{dE}{dN_t}$, where $N_t$ is the number of nuclei per unit target area. The energy loss in the target also determines the effective interaction energy:

$$E_{eff} = \frac{\int_{E_b-\Delta E_b}^{E_b} E \cdot \sigma(E) dE}{\int_{E_b-\Delta E_b}^{E_b} \sigma(E) dE}. \quad (2)$$

An extensive investigation of all quantities in Eq. (1) showed the systematic uncertainty in the determination of the cross section to be about 4% [7].

Measurements were performed at seven energies between $E_{lab}$= 2999.6 to 6526.6 keV selecting in all cases the charge state 3+ for the $^8B$ recoils. The energy range and the number of data points were limited by the available amount of $^7Be$. The $\Delta E - E$ telescope was calibrated using a low intensity mixed $^7Li - ^7Be$ beam transported to the final detector. The resulting $\Delta E - E$ is shown in Fig. 1 with a gas pressure P=6.0 mbar. Measurements on the resonance lasted typically a few hours, while measurements off resonance lasted three to five days. The areal density was controlled with a precision of 0.2% and a reproducibility of 0.1% using a capacitive manometer (Pfeiffer CMR) and a computer control system to stabilize the gas pressure. The target gas was hydrogen 6.0, i.e. with a purity better than 99.9999%. The calibration matrix is compared with a Monte Carlo simulation using the code LISE++ [11]. The detector effective lengths in the simulation were adjusted within 5% of their geometrical values to fit the calibration, as shown in Fig. 1, where a $3\sigma$ contour plot represents the simulation results for the mixed $^7Li - ^7Be$ beam ions. The simulation code has been later used to predict the position and width of the regions where recoils and "leaky" beam ions are expected to appear, taking into account the actual gas pressure in the chamber, that was varied between 3.6 and 8.0 mbar to optimize the detection of the recoils. Fig. 2 shows the matrices collected on top of the resonance

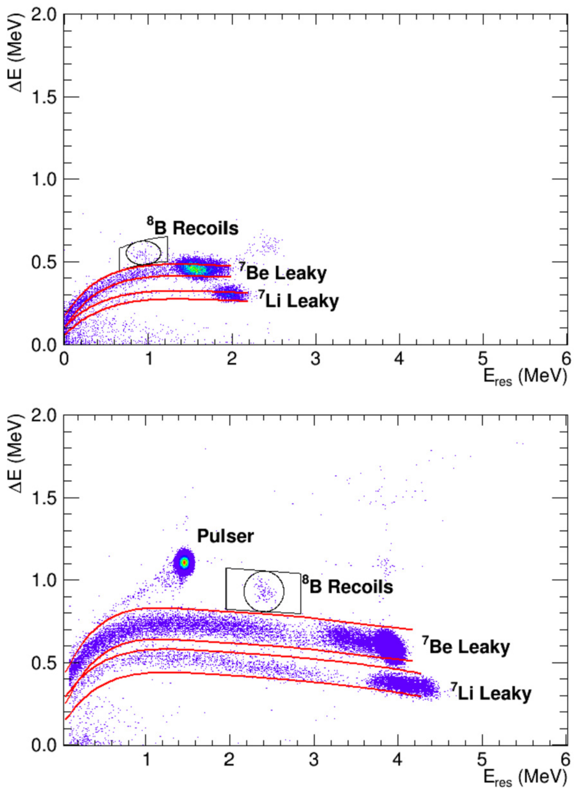


**Fig. 2.** $\Delta E - E_{res}$ matrices of the end detector of ERNA for $^7$Be(p, $\gamma$)$^8$B at $E_{eff}$=367.2 keV (top panel) and 632.2 keV (bottom panel). Both $^7$Li and $^7$Be "leaky" beam ions are visible with their long low energy tails. The contour plots represent the predictions of a Monte Carlo simulation for the different ion species. The rectangular region around the elliptical area where the $^8$B recoils are expected is used to estimate the background. Signals produced by a pulser were used for monitoring signal formation and acquisition. See text for details.

at $E_{eff}$=632.2 keV (bottom panel) and at the lowest investigated energy $E_{eff}$=367.2 keV (top panel). In both cases, matrices are shown without any threshold on the number of counts, demonstrating the excellent suppression of the incident beam ($10^{-9}$ and $10^{-10}$ respectively). In the matrices the regions determined using LISE++ are also shown. For the $^8$B recoils, a circular contour identifies the region where the reaction products are expected, while a rectangular region around it represents the region used to evaluate the background. The background correction turned out to be below 3% at all energies. During the measurements occasional instabilities of the voltage across the electric plates of the Wien Filters produced an increase of the leaky projectile ions reaching the final detector. In other occurrences the beam was lost because of instabilities at the accelerator HV terminal. These events resulted in a marked increase or decrease in the trigger rate, respectively, and were excluded from the analysis. The total fraction of discarded data was below 1% at all energies, whereas this procedure cannot produce any bias in the determination of the reaction yield. Table 1 reports the results of the present work in numerical form. The cross section is extracted from the observed yield $N_r/N_b$ using equations (1) and (2), where the energy dependence of $\sigma(E)$ of [3] is assumed. The effective interaction energy was calculated assuming the same energy dependence. The target thickness $\Delta E_b$ is obtained from the experimental values reported in [7], corrected by a factor 0.9 to account for the $^7$Be energy loss in the Ar gas layers confining the $^1H_2$ target, not considered in [7]. Fig. 3 shows the results of our experiment compared to previous measurements in form of astrophysical S-factor:

**Table 1**
Results of the measurements performed in the present work. The quoted uncertainties are statistical only. Yields and cross sections are affected by an overall systematic uncertainty of 4%. The beam energy has a systematic uncertainty of 0.06%.

| $E_b$ (keV) | $\Delta E_b$ (keV) | Yield ($10^{-12}$) | $E_{eff}$ (keV) | $\sigma$ (μb) | $S_{17}$ (eV · b) |
|---|---|---|---|---|---|
| 375.9 | 18.3 | 0.63±0.10 | 367.2 | 0.087±0.014 | 14.7±2.3 |
| 617.0 | 15.8 | 5.1±0.8 | 610.5 | 0.72±0.11 | 51.2±8.0 |
| 640.2 | 15.6 | 8.7±0.9 | 632.2 | 1.27±0.13 | 86.1±9.0 |
| 640.2 | 15.6 | 8.9±1.1 | 632.2 | 1.29±0.15 | 87.2±10.5 |
| 640.6 | 15.6 | 9.2±1.9 | 632.5 | 1.34±0.28 | 90.9±19.0 |
| 675.5 | 15.2 | 3.0±0.6 | 667.2 | 0.41±0.08 | 25.9±5.1 |
| 705.6 | 14.8 | 2.5±0.9 | 697.8 | 0.34±0.12 | 20.0±7.4 |
| 707.6 | 14.8 | 3.8±1.1 | 699.8 | 0.52±0.15 | 30.7±9.0 |
| 819.0 | 13.6 | 3.7±0.7 | 812.2 | 0.51±0.10 | 25.3±5.1 |

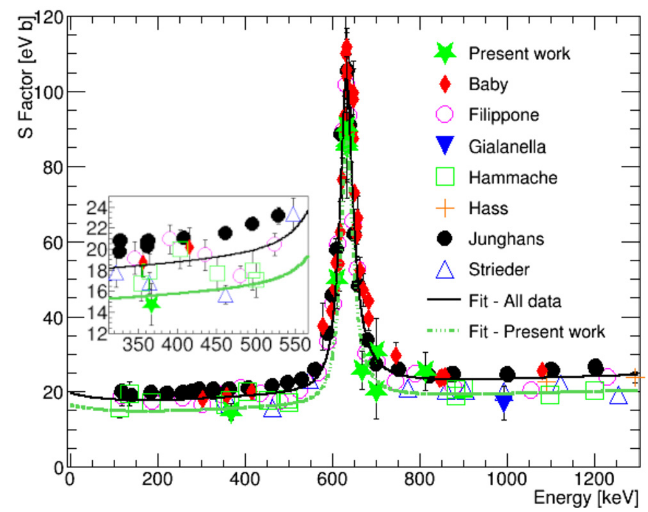


**Fig. 3.** S-factor values obtained in the present work compared to [4,14–23]. The solid black line represents a fit to all data sets considering the inflation of the systematic uncertainties to obtain a statistical compatibility. The solid green line represents the fit to the data presented here alone. The insert highlights the energy range where a structure appears in some data sets. See text for details.

$$S(E) = E\sigma(E)e^{2\pi\eta}, \tag{3}$$

where the Sommerfeld parameter $\eta$ is given by:

$$2\pi\eta = \frac{Z_1 Z_2 e^2}{\hbar v} = 117.49 \cdot E^{-1/2},$$

with E in keV. Data are compared to a fit function including a non resonant component as given in [12] and a resonant component, with the energy dependent widths $\Gamma_p$ and $\Gamma_\gamma$ calculated using the approximations given in [13].

One should note that our measurement is marginally compatible with the data of Junghans et al. [21–23] and Baby et al. [15,16], while it is in good agreement with all other measurements. In addition, there is a remarkable discrepancy between the results of [21–23] and all other existing data around E=450 keV, as highlighted in Fig. 4. In this region existing data, with the exception of [21–23], appear to indicate a pattern that, if confirmed, could indicate either an interference with higher lying resonances, or an interference of the direct capture with a weak resonant capture to a hypothetical negative parity state blended by the strong resonance at E=630 keV. Whatever the origin, the remarkable fact remains that the discrepancy between the data sets seems also to extend to some aspects of the energy dependence and not just the absolute scale of the cross section. Unfortunately, the available $^7$Be beam and the low cross section did not allow further measurements in this energy region, that will be investigated in future experiments.

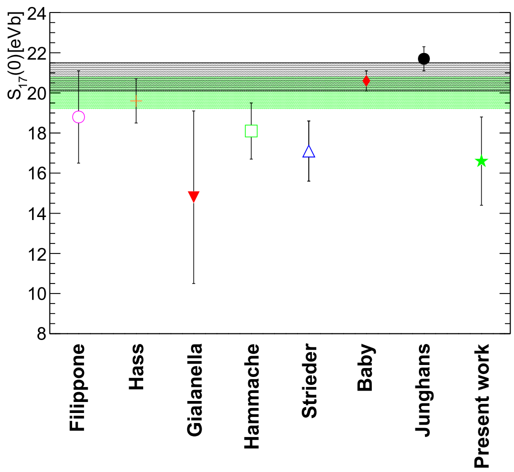


**Fig. 4.** $S_{17}(0)$ values obtained fitting each data set shown in Fig. 3. The error bars include systematic errors. The results of [21–23] are summarized in a single point, since they originate from the same experiment. The same holds for the results of [17] and [18]. The green shadowed band indicates the value $S_{17}(0)=20.0\pm0.8$ eV·b we suggest here. The hatched band indicates the frequently used recommendation of [3], $S_{17}(0)=20.8\pm0.7$ eV·b. See text for details.

Fig. 4 shows a plot of the results of this work and previous measurements in form of the extrapolated S-factor at zero energy $S_{17}(0)$, where the error bars include systematic errors. All data sets are analyzed using the fit function described above, where only data at $E\leq1300$ keV are taken into consideration. A fit to our data alone yields $S_{17}(0)=16.6\pm2.1$ eV·b. It is interesting to note that, although an overall discrepancy is observed, data sets group in statistically compatible subsets, indicating that the origin of the discrepancy is most likely to be found in wrong estimates of common effects (normalization factor, detection efficiency, target thickness) determining the systematic uncertainties rather than in the statistical uncertainties of the single data points. As a consequence, we propose to apply the inflation factor method [24] to the systematic uncertainties alone, multiplying the quoted systematic uncertainties by a common factor to obtain equal internal and external errors on the mean, where the internal error is calculated including both statistical and systematic errors. This procedure provides a good fit of all data with an estimate $S_{17}(0)=20.0\pm0.8$ eV·b.

## 3. Results and conclusions

The total cross section of $^7$Be(p, $\gamma$)$^8$B was measured in the energy range $E_{eff}$=367.2 keV to 812.2 keV using a radioactive $^7$Be beam and a recoil mass separator. For the first time, this approach provides results with adequate precision to determine the cross section of $^7$Be(p, $\gamma$)$^8$B at astrophysical energy. Our results are compatible with the currently mostly used value $S_{17}(0)=20.8\pm0.7$ eV·b [3] only at a 2-$\sigma$ level, thus strengthening the discrepancy between existing data sets. A global fit to our data and all data sets selected in [3] provides an estimate $S_{17}(0)=20.0\pm0.8$ eV·b, where systematic uncertainties were inflated to obtain statistically compatible data. This suggestion, like all estimates given above, represents the commonly used 68% compatibility range.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2021.136819.

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